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A comparison of center of pressure variables recorded during running in barefoot, minimalist footwear, and traditional running shoes in the female population

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In recent years, barefoot running and running in minimalist footwear as opposed to running in traditional running shoes has increased in popularity. The influence of such footwear choices on center of pressure (COP) displacements and velocity variables linked to injuries is yet to be understood. The aim of this study was to investigate differences between COP variables, linked to injuries measured in barefoot running, a minimalist running shoe, and with traditional running shoes and conditions during running in a healthy female population. Seventeen healthy female participants were examined. Participants performed five footfalls in each footwear condition while running at 12km/h±10% over a pressure plate while COP variables were recorded at 500Hz. The results suggest that minimalist running shoe COP characteristics were similar to those of barefoot runners, with various significant differences reported in both groups compared to runners with the traditional running shoe.

Keywords: footwear, barefoot, running, COP, center of pressure, plantar pressure

Following the introduction of running specific footwear, in recent years barefoot (BF) running as opposed to running in traditional running shoes (TRS) with elevated cushioned heels has increased in popularity among participants and coaches [1]. When running barefoot on roads or pathways the plantar region of the foot may be exposed to cuts and general discomfort from debris and uneven surfaces, therefore running in minimalist footwear that may allow for the change in running kinetics and kinematics observed in barefoot running compared to shod while protecting the plantar region of the feet from injury and discomfort appears to be desirable.

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This has led to a rise in the popularity of barefoot inspired footwear amongst running populations and subsequent research [2]. Running barefoot does not appear to restrict athletes from competing at an elite level, with competitors winning Olympic medals in such conditions. In terms of energy cost to the runner, running barefoot appears to reducing angular inertia of the lower extremities. Research suggests minimalist shoes may also decrease oxygen consumption during running [3,4]. However, recent research suggests there is no reduction of metabolic cost when running barefoot compared to lightweight running shoes [5].

Some research suggests that wearing traditional running shoes may restrict freedom of movement and flexibility that can be achieved in comparison to barefoot running [6]. Furthermore, running barefoot compared to shod has been identified as causing adaptation in running mechanics, resulting in a more midfoot footfall in contrast to a favored heel striking movement strategy while running in traditional running shoes [2,7]. Research also suggests that such adaptations occur instantaneously with only minor changes in the lower extremity kinematics observed in the reported knee angle after two weeks of training in minimalist footwear [8]. Such adaptations observed in barefoot running have been proposed as a mechanism by which the potentially detrimental loading imposed upon the musculoskeletal system during running may be attenuated [9–11]. Conflicting research has however reported such increases in loading of the musculoskeletal system in barefoot running compared to shod, in participants who habitually wore shoes [12,13]. Furthermore, foot injuries including stress fractures most prominently in the metatarsals have been reported in minimalist shoe runners [14]. Currently there appears to be a lack of evidence confirming the influence of barefoot running on movement strategy and injury rates [15,16].

Research identifying the influence of footwear conditions should initially focus on areas of greatest injury risk within the musculoskeletal system which research suggests is ankle ligament damage [17]. The ankle joint is unique in that the vast majority of injuries sustained across different populations are of one type; ligament sprains [17–21]. It is worth noting that such injury rates in females [22] are higher than those of males [23].

The reason for the higher occurrence of ankle sprains while running can only be hypothesized. Research has suggested that during running the ankle is often placed in a compromised supinated position when the athlete's center of gravity (COG) is positioned over the lateral border of the weight bearing limb [24,25]. It has been identified that the functionally unstable ankle may be the result of proprioceptive neuromuscular deficits arising from structural damage following an injury [26–29].

Various kinetic and kinematic variables have been investigated to compare differences between barefoot and shod conditions. However there is a paucity of research investigating the differences in center of pressure (COP) variables between the conditions [16]. Plantar COP velocities and displacements measured during running have been identified as indicators of exercise induced lower leg injuries [30,31]. As such, identifying characteristics of the COP have been identified as suitable reference points for studying the dynamics of the rearfoot and foot function [31,32] and to identify differences in footwear conditions [33]. Studies analyzing the gait of those individuals with functional unstable ankles have identified a tendency for a laterally situated COP on initial foot contact with a greater pressure concentration at the lateral aspect of the heel [26,30]. If the COP is focused to the lateral side of the calcaneus during heel strike, it is possible that the additional force required to place the individual into a compromised position may be minimal [30]. As a result, by examining the location of the COP upon initial contact it may be possible to identify running conditions that could potentially reduce the likelihood of sustaining a lateral ankle sprain by avoiding the COP displacements seen in the unstable ankles.

A commercially available design of minimalist design footwear (huaraches (HU)) have been developed (Figure 1) with minimum cushioning (4mm tread) and string uppers designed to minimally restrict natural foot movement. By comparing COP variables in participants running barefoot and wearing the HU footwear it may be possible to see the different foot mechanics in each. Therefore the aim of this study was to investigate the differences between COP variables, many of which are linked to ankle ligament injuries, measured in barefoot, huaraches and traditional foot wear runners (Figure 1). The differences in kinetics and kinematics measured between genders [19,34–37] demonstrates a need for studies investigating kinetics of locomotion to consider each gender separately and as such this research will focus on conditions during running in a healthy female population.

Methods

Selection and Description of Participants

Seventeen healthy female participants were examined (aged 21.2±2.3 years, height 165.4±5.6 cm, body mass 66.9±9.5 kg, foot size 6.8±1.0 UK). All participants were free from musculoskeletal pathology and provided written informed consent in accordance with the declaration of Helsinki.

Figure 1 HU footwear (above) and TRS (below).

Technical Information

Participants were given time to practice running in the minimalist footwear until they felt comfortable, no prior training was undertaken [8]. Participants performed five footfalls in each footwear condition at a controlled speed of 12km/h±10% over a Footscan pressure plate (RsScan International, 1m x 0.4m, 8192 sensors) (Figure 1) collecting COP data at 250Hz positioned in the center of a 28.5m runway. Participants practiced running along the runway and adjusted their starting position to achieve a natural footstrike on the pressure mat to minimize any influence of targeting [38]. They were also instructed to look at a point on the far wall and not slow down until passing the second timing gate.

Various times (Initial Metatarsal contact (IMC), initial forefoot flat contact (IFFC, first instant all the metatarsals heads are in ground contact) and heel off (HO)) during foot to ground contact were identified (Fig.2), anterior-posterior and medial-lateral displacement and velocity data were calculated at these time points [30,39]. COP displacement and velocity values were normalized to a percentage of foot width and length as appropriate and using the same methods as in previous research [30,39]. This method of collecting COP progression data in direct foot contact and under the shoe has been confirmed as reasonable [40,41].

Statistics

Descriptive statistics including means and standard deviations were calculated for each COP variable in each condition. One way repeated measures ANOVAs were used to determine the differences between footwear conditions with significance accepted at the $p<0.05$ level. The Shapiro-Wilk statistic for each condition confirmed that the data were normally distributed and where the sphericity assumption was not met, correctional adjustment was made using Greenhouse-Geisser. Effect sizes were calculated using an Eta^2 (η^2). Post-hoc analyses were conducted using a Bonferroni correction to control type I error (Table 1). All statistical procedures were conducted using SPSS 19.0 (SPSS Inc., Chicago, IL, USA).

Results

The COP data collected was observed for each trial and various key points in time during the stance phase were identified (Figure 2)

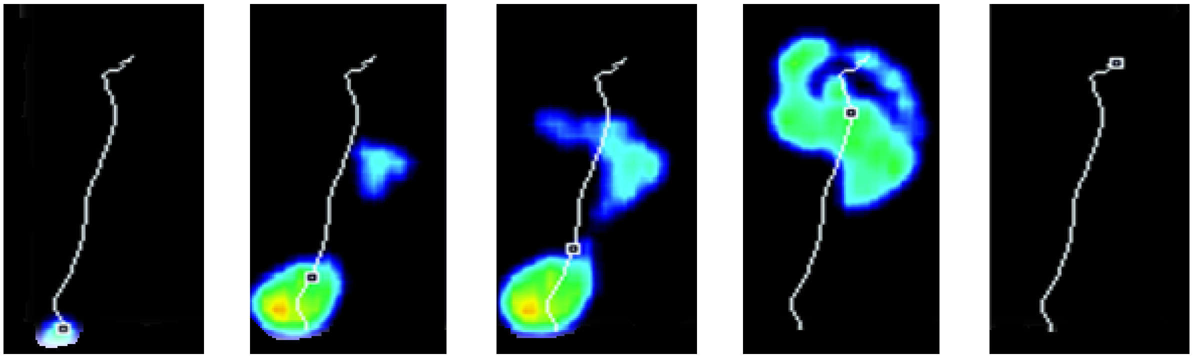

Figure 2 Typical BF plantar pressure.

The means were calculated for the COP timing (Table 1), COP medial-lateral (Table 2) and COP anterior-posterior (Table 3) variables.

Time variables

Analysis of the timing variables reported between the footwear conditions is displayed in Table 1 and indicated a significant main effect for the timing of IMC ($F_{(1.41,\ 22.55)}$= 57.29, $p<0.0005$, η^2=0.782) and IFFC ($F_{(2,\ 32)}$= 43.69, $p<0.001$, η^2=0.732) no significant effect was reported for HO ($F_{(1.30,\ 20.87)}$= 2.56, p=0.118, η^2=0.138). Post hoc analysis revealed significant differences ($p<0.001$) between the TRS and both the BF and HU conditions for timing of IMC, This was also the case for the IFFC event timing which additionally reported a significant difference (p=0.04) between the BF and HU conditions.

Footwear Condition	BF	HU	TRS
IMC time (ms)	13.0±5.0	13.3±4.8	30.8±11.6$^{†¥}$
IFFC time (ms)	20.0±7.3	24.9±11.1†	39.0±12.5$^{†¥}$
HO time (ms)	119.3±19.5	125.9±18.6	125.3±21.5

Table 1 Means and standard deviations of center of pressure variables timing variables. †=Significantly different ($p<0.05$) from BF, $^{¥}$=significantly different ($p<0.05$) from HU, *=significantly different ($p<0.05$) from TRS.

Medial Lateral COP Variables

Analysis of the movement of the COP in the Medial Lateral plane of the foot between footwear conditions are displayed in Table 2 and report that a significant main effects for the position of the COP in terms of medial lateral position (X-comp) were identified at IMC X-comp ($F_{(1.454,\ 23.268}$= 5.87, p=0.014, η^2=0.269), IFFC X-comp ($F_{(2,\ 32)}$= 18.9, $p<0.001$, η^2=0.542) and HO X-comp ($F_{(2,\ 32)}$= 15.6, $p<0.001$, η^2=0.494).) No significant main effect was identified for IFCX-comp ($F_{(2,\ 32)}$ = 3.161, p=0.056, η2=0.165). Post hoc analysis revealed a significant difference for IMC X-comp (p=0.025), IFFC X-comp (p=0.001) and HO X-comp (P=0.003) between BF and TRS conditions, and a significant difference between IFFC X-comp ($p<0.001$) and HO X-comp ($p<0.001$) between HU and TRS conditions.

Significant main effects for the position of the medial lateral velocity of the COP in terms of position (VEL-X) were identified for HO VEL-X ($F_{(2,\ 32)}$ = 32.6, $p<0.001$, η2=0.671). Post hoc analysis revealed a significant difference for HO VEL-X between BF and TRS ($p<0.001$) and HU and TRS ($p<0.001$). No significant main effect was identified for IMC VEL-X ($F_{(1.46,\ 23.31}$= 1.314, p=0.279, η^2=0.076) or IFFC VEL-X ($F_{(1.33,\ 21.24)}$ = 2.073, p=0.161, η2=0.115).

Footwear Condition	BF	HU	TRS
IFC X-comp (FW %)	14.4±15.4	14.0±14.4	20.9±9.6
IMC X-comp (FW %)	11.2±8.7	10.1±10.3	6.0±7.3†
IFFC X-comp (FW %)	11.0±6.3	12.2±6.8	4.5±5.7†¥
HO X-comp (FW %)	4.3±3.6	5.0±2.8	1.8±3.5†¥
IMC VEL-X (FW%/ms)	.084±.69	.0514±.66	-.136±.57
IFFC VEL-X (FW%/ms)	-.25±.33	-.159±.28	-.328±.39
HO VEL-X (FW%/ms)	-.154±.06	-.135±.06	-.043±.054†¥

Table 2 Means and standard deviations of center of medial-lateral pressure variables. †=Significantly different (P<0.05) from BF, ¥=significantly different (p<0.05) from HU, *=significantly different (p<0.05) from TRS, FW%=Percentage of foot width.

Footwear Condition	BF	HU	TRS
IFC Y-comp (FW%)	28.7±21.8	21.4±18.9	15.1±20.0
IMC Y-comp (FL%)	33.8±16.5	28.7±16.1	35.7±12.9
IFFC Y-comp (FL%)	40.0±12.5	43.3±18.9	45.3±9.5
HO Y-comp (FL%)	70.3±3.0	70.1±5.2	79.5±4.3†¥
IMC VEL-Y (FL%/ms)	.640±.93	.734±.75	1.36±.70†¥
IFFC VEL-Y (FL%/ms)	.344±.70	.454±0.41	.649±.52
HO VEL-Y (FL%/ms)	.144±.08	.143±.08	.2248±.07†¥

Table 3 Means and standard deviations of anterior-posterior center of pressure variables.†=significantly different (p<0.05) from BF, ¥=significantly different (p<0.05) from HU, *=significantly different (p<0.05) from TRS, FL%=Percentage of foot length.

Anterior Posterior COP Variables

Analysis of the movement of the COP in the Anterior Posterior plane of the foot between footwear conditions are displayed in Table 2 and report that a significant main effects for the position of the COP in terms of anterior posterior position (Y-comp) were identified at IFCY-comp ($F_{(2, 32)} = 5.04$, $p<0.013$, $\eta^2=0.239$) and HO Y-comp ($F_{(1.09, 17.39)} = 30.71$, $p<0.001$, $\eta 2=0.657$). No significant main effect was identified for IMC Y-comp ($F_{(1.42, 22.66)} = 3.28$, $p=0.07$, $\eta^2=0.170$) or IFFC Y-comp ($F_{(1.22, 19.58)}= 0.88$, $p=0.38$, $\eta^2=0.052$). Post hoc analysis revealed a significant difference for HO Y-comp ($p<0.001$) and IFC Y-comp ($p=0.025$) between BF and TRS, a significant difference was also identified for HO Y-comp between HU and TRS conditions ($p<0.001$).

Significant main effects for the position of the anterior posterior velocity of the COP in terms of position (VEL-Y) were identified for IMC VEL-Y ($F_{(1.41, 22.58)}= 13.60$, $p<0.0005$ $\eta^2=0.460$) and HO VEL-Y ($F_{(1.17, 18.77)}= 13.26$, $p=0.001$, $\eta^2=0.453$) No significant main effect was identified for IFFC VEL-Y ($F_{(1.21, 19.33)}= 1.710$, $p=0.209$, $\eta^2=0.097$). Post hoc analysis revealed a significant difference between BF and TRS for IMC VEL-Y ($p=0.005$) and HO VEL-Y ($p=0.001$), significant differences were also identified between HU and TRS for IMC VEL-Y ($p=0.002$) and HO VEL-Y ($P=0.011$).

Discussion

The purpose of the current investigation was to compare the COP variables of a healthy female population running in BF, HU and TRS conditions. The first aim was to identify if there existed any differences between the shod and BF conditions, in order to identify whether running in such footwear produced similar kinetics to those found in BF running. The second aim was to determine if there were any significant differences between footwear in the COP variables implicated in the etiology of injury [30].

The significant differences in the IMC and IFFC time parameters ($p<0.05$) in the TRS compared to the BF and HU conditions, suggest a more plantarflexed foot placement (in BF and HU) at ground contact. This has been reported previously in analyses comparing BF to shod [2,12] and minimalist footwear compared to shod [3] conditions and suggests HU rather than TRS would be the favored footwear to reduce the incidence of injury in runners [10–12]. During running there is often uneven terrain, and as the calcaneus lands, it lends itself to movement in the coronal plane by the very nature of its shape. Furthermore, it has been identified that patients with ankle instability have a longer duration of contact from the initial heel contact to the forefoot landing

[42]. Therefore, a quicker loading of the forefoot as observed in the BF and HU conditions, may offer greater support to potentially limit hazardous injury.

During locomotion, as the foot makes contact with the ground, the line of the resulting reaction force is determined by the position of the foot in relation to the athletes COG [24]. Previous research reported that when an increased angle of supination upon touchdown was present, an apparent increase in the number of ankle sprains ensued [43]. With the TRS condition in the current study exhibiting a trend towards a more laterally displaced COP, this may infer that the initial contact of the foot was made whilst being held in slight supination, and therefore similar those suffering from ankle instability which may increase susceptibility to injury.

Previous research identified that an ankle sprain group exhibited a higher loading under the medial border of the foot, and this was identified as an indicator or susceptibility to ankle sprain [30]. The significant difference between the shod and both the BF and HU condition for the IFFC X-comp variable indicated a more medially loaded foot. This may also be a predisposing factor for an inversion ankle sprain.

It appears that the HU shoe minimizes the changes in COP characteristics seen in TRS compared to BF running with only one variable (IFFC time) reporting a significant ($p<0.05$) difference between HU and BF. Furthermore, this particular minimalist design (HU) may more closely simulate BF running compared to some other footwear designed to simulate BF running [2]. These results suggest that proposed health benefits associated with BF running [10] may be prevalent in HU footwear conditions.

Conclusions

The data collected in this study provides evidence that the HU design of footwear may be a suitable alternative to running BF for females, by offering protection to the plantar surface of the foot whilst adjusting the running strategy identified through COP variables in a similar way to BF running when compared to running in TRS. From a rehabilitation point of view, it may advantageous to initiate a return to running using minimalist footwear as this appears to have the potential to reduce excessive COP characteristics linked to ankle inversion injury compared to shoes. However potential injury risk reduction benefits of BF running are yet to be conclusively substantiated and any change in habitual running style through footwear choice should be approached with caution.

Future research

This study focused on a population of healthy females. Previous research has demonstrated differences between genders biomechanically and regarding injury rates [19,44] and as such the results cannot be generalized to a male sample. Therefore there is clear need to perform a similar examination using a male population. Previous research has suggested that the thickness of cushioning in running shoes may not have a significant effect on loading characteristics [7] during foot to ground impact. The HU design of shoe is commercially available in different sole thickness. Testing for similar effects of sole thickness that are observed in the HU design of shoe warrant further investigation to identify a move towards the possibility for an optimum design in the general population.

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